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Foamed Polystyrene in the Marine Environment: Sources, Additives, Transport, Behavior, and Impacts

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Abstract

Foamed polystyrene (PS) that may be either expanded (EPS) or extruded (XPS) is a rigid, lightweight insulating thermoplastic that has a variety of uses in the consumer, packaging, construction, and marine sectors. The properties of the material also result in waste that is readily generated, dispersed, and fragmented in the environment. This review focuses on foamed PS in the marine setting, including its sources, transport, degradation, acquisition of contaminants, ingestion by animals, and biological impacts arising from the mobilization of chemical additives. In the ocean, foamed PS is subject to wind-assisted transport and fracturing via photolytic degradation. The material may also act as a substrate for rafting organisms while being exposed to elevated concentrations of natural and anthropogenic surface-active chemicals in the sea surface microlayer. In the littoral setting, fragmentation is accentuated by milling in the swash zone and abrasion when beached, with wind transport leading to the temporary burial of significant quantities of material. Ingestion of EPS and XPS has been documented for a variety of marine animals, but principally those that feed at the sea surface or use the material as a habitat. As well as risking injuries due to gastro-intestinal blockage, ingestion of foamed PS exposes animals to harmful chemicals, and of greatest concern in this respect is the presence of the historical, but still recycled, flame-retardant, hexabromocyclododecane. Because foamed PS is particularly difficult to retrieve as a constituent of marine litter, means of reducing its presence and impacts will rely on the elimination of processes that generate foamed waste, modification of current storage and disposal practices, and the development of more durable and sustainable alternatives.

1. Introduction

Marine pollution from plastics has received an enormous amount of scientific, media, and public attention over the past two decades. Studies on plastics have focused on methods of sampling, sources, distributions, impacts on the environment and on wildlife, and the uptake of pollutants, with a number of reviews that attempt to synthesize research in each area or a combination of areas (1-4). For materials of comparable bulk characteristics (e.g. size, density, and crystallinity), distributions, sinks, and physical impacts are expected to be broadly similar and in most review articles plastics or microplastics are explicitly or implicitly defined under a single umbrella. For foamed plastics, however, densities are so much lower than unfoamed equivalents that their behavior is distinctly different and they should, strictly, be classified independently.

In the present paper, the focus is on one of the most important and widely used types of foamed plastic, polystyrene (PS). This material is a common component of marine litter and is particularly problematic from both a local and transboundary perspective (5-9). Information and data are critically reviewed in the scientific literature on the sources, chemical composition, transport, fate, and impacts of foamed PS in the marine environment. Where informative, comparisons are also made with (unfoamed) polyethylene, another common component of marine litter whose greater density ensures its pathways and behavior are markedly different from foamed PS. The more general challenges associated with the generation and disposal of large quantities of foamed PS in society are addressed, and current and proposed solutions to these problems are reviewed.

2. Foamed PS: Production, uses, waste, and marine littering

PS is a rigid, amorphous thermoplastic produced by free radical vinyl polymerization of styrene. The structure of the polymer can be written thus: $[CH_2CH(C_6H_5)]_n$; where C_6H_5 is a pendant phenyl group which restricts rotation and is responsible for many of the physical and mechanical properties of the polymer. Both expanded PS (EPS) and extruded PS (XPS) are forms of the polymer that contain a high proportion of air (> 95%) (10, 11). EPS is produced when the raw, pelletized material is expanded by heating with steam to form cellular beads. Dried particles are then fused under steam and molded into blocks or other shapes, with beads of 2 to 5 mm in diameter clearly visible in the final product. The air within and between the beads gives EPS its insulating properties but inter-particle air, as irregular gaps or voids, renders the material susceptible to (limited) water absorption. XPS is formed when PS crystals, additives, and blowing agents are extruded at high temperature to produce a frothy liquid that is subsequently shaped in a die as it cools and expands. XPS consists of tightly

packed cells that have no gaps or voids between them. This closed structure inhibits water absorption and results in a smoother surface and a higher density than EPS. Note that Styrofoam® is often used synonymously with foamed PS but is, strictly, a trademarked brand of XPS produced for building insulation by Dow Chemical.

Foamed PS is commonly employed in home and appliance insulation, protective packaging, automobile parts, embankment filling, lightweight concrete (as an aggregate), and food packaging (11;12); with regard to the construction sector, XPS is favored over EPS where pressure, stability, and humidity are especially high (13). The durability, low density, and insulating properties of foamed PS have also resulted in many applications in the marine sector. Here, EPS (and less frequently, XPS) are used in fish boxes, buoys, pontoons, floating docks, net floats, life jackets, surfboards, and boat stands (14-17). As a tethered floating base, EPS is used directly, or for greater durability, may be coated or covered by hard plastic or cement (13).

Because of its growing demand and extensive on land and at sea, coupled with recycling that is constrained by its bulk and contamination (by food, for example), foamed PS represents an important form of waste. European data for 2016/2017 suggest that waste generation of foamed PS from construction and packaging was about 530,000 tonnes, with a recycling rate of 27% in total for EPS (and 34% for single use packaging waste and 8% for construction waste) and energy recovery by incineration as the most common method for its disposal (13).

Loss of foamed PS to the environment may occur via the transport, storage, or cutting of construction material, escapement of waste from controlled and historical landfill, storage or compaction of waste before or during disposal or recycling, deterioration or loss of structures in situ, and littering and fly tipping. Waste enters the marine environment through rivers, stormwater, and wastewater treatment plants, and from direct littering and loss or structural damage at sea or in the littoral zone. Not only is foamed PS a significant contributor to marine litter worldwide (9;18-24), its lightness and low density, ready transportation by the wind, and propensity to readily fragment ensure that it disperses more widely and rapidly than other forms of (unfoamed) plastic, both at sea and when beached (8;25;26). With small fragments readily blown around by the wind when dry and adhering to surfaces when wet, foamed PS is also particularly difficult to retrieve during beach cleans.

The images in Figure 1 exemplify some of the uses of foamed PS that may directly impact on the marine environment, along with the volume, nature, and consequences of secondary (fragmented) particles that can be readily washed up and blown around. Material illustrated here ranges in size from EPS beads of a few mm in diameter to slabs greater than 1 m across. However, empirical

studies suggest that, ultimately, weathering may produce spherical and elongated particles of dimensions down to hundreds of nm (27).

3. Transport and physical behavior in the marine environment

The properties of foamed PS that are of relevance to its behavior and fate in the marine environment are shown in Table 1. Here, data are indicative and are based on the properties of a specific brand or a range of brands of EPS, which is far better characterized than XPS in the literature. Note, however, that in general, XPS has a slightly higher density, greater tensile, impact, and compressive strengths, and lower water absorption than EPS (28).

3.1. In the ocean

The following discussion focuses on floating and fragmented foamed PS in the ocean, with the effects and forcing mechanisms acting upon this type of litter conceptualized in Figure 2 as an aid to the narrative.

One of the key differences in the transport plastics having a density slightly lower than seawater (like polyethylene without any inclusions of air) to those having a density significantly lower than seawater and floating at the surface (foamed plastics) is the influence of windage, or drift due to wind forces (31). Specifically, and neglecting any phenomena incurred by viscous forces, wind pressure acting on the upper ('sail') surface of a particle is opposed by the drag force applied to its lower, submerged ('drag') surface, with the ratio of sail and drag surface areas dependent on particle and fluid densities and determining the magnitude of windage. The high buoyancy of foamed PS also confers a relatively low floating stability, especially if objects are rounded. Thus, because the center of gravity is well above the sea surface, objects tend to repeatedly change position and orientation during transportation (33).

The effect of windage on the ocean transport of foamed PS of density = 0.05 g cm^{-3} and polyethylene of density = 0.95 g cm^{-3} was considered theoretically by Chubarenko et al. (32). Specifically, calculations were performed for spherical particles (of any diameter) carried in inviscid (Baltic) seawater of density ~ 1.01 g cm^{-3} and with a current speed, v_c, of 0.3 m s^{-1} that were subject to a wind blowing in the same direction at a speed, v_w, of 10 m s^{-1}. The drift speeds for PS and polyethylene, v_{PS} and v_{PE}, were estimated to be about 1.2 m s^{-1} and 0.4 m s^{-1}, respectively, or four times and 25% higher than v_c. In other words, and under these environmental conditions, foamed PS

whose density is not significantly modified by fouling (see below) is predicted to travel three times faster in seawater than polyethylene.

An additional consequence of foamed PS residing at the sea surface is that it is exposed to a greater amount of sunlight than plastics that are less buoyant and, through turbulence, are transported in the bulk medium (34). Moreover, the aromatic backbone of PS acts as effective absorber of solar radiation in the ultraviolet (UV) region (35). Absorption of sunlight causes cleavage of polymer chains by chain scission, with styrene monomers the principal product of degradation (36). Resulting embrittlement of the foamed PS surface causes fracturing and, eventually, fragmentation (8). Experiments performed by Song et al. (37) showed that two months of exposure to UV light generated by a metal-halide lamp was sufficient to break EPS beads (~ 20 mm^3) into microfragments, thereby exposing new surfaces to UV radiation and promoting further degradation. A recent study conducted by Zhu et al. (38) compared the degradation of post-consumer EPS under simulated solar radiation with that of other plastics (including polyethylene). Based on mass loss over the experimental period employed, the authors estimated lifetimes of 2.7 years for EPS and 33 years for polyethylene. By comparison, microbial biodegradation of foamed PS can be considered almost negligible over such timeframes (39).

3.2. In the littoral zone

Ultimately, a significant fraction of both oceanic and land-derived foamed PS will end up in the littoral zone, including mangroves, beaches, and rocky shores (19;20;24). The effects and forcing mechanisms acting upon this type of litter on a sandy shoreline are conceptualized in Figure 3 as an aid to the following discussion.

When beached, both photolytic and thermal degradation of foamed PS are accentuated because significantly higher temperatures are possible in sand compared with seawater (8). Moreover, mechanical fragmentation is highly favorable here because wind-driven transport engenders frictional forces and collisional impacts on material of inherently low tensile strength (Table 1). For example, experiments that exposed EPS beads to UV radiation under a metal-halide lamp for twelve months and subsequently subjected them to mechanical abrasion (through agitation with sand) resulted in the majority of the original particle volume becoming fragmented to sizes too small (< 1 μm) to be detected (37;40).

Mechanical fragmentation of foamed PS also takes place in the swash zone where litter already weakened by photolytic processes is “milled” with sand and pebbles as it is transported under

dynamic, asymmetrical wave motion. Chubarenko and co-workers (41;42) conducted experiments in which plastics, including EPS, were subject to simulated swash conditions for 24 h in the presence of sand, gravel, and pebbles. Results revealed that material was smoothed, polished, torn, and fragmented into beads and that, although impaction of EPS with pebbles was low compared with other plastics because of the high buoyancy of the material, these interactions resulted in the greatest number of fragmented particles. Significantly, despite the low density of EPS, some beads formed on fragmentation became attached to or trapped-buried by the sediment. The burial and subsequent compaction of EPS beads also appears to take place on more landward reaches of a beach. Here, material blown against a physical barrier along with other light plastics is subsequently buried by accumulations of drifting sand.

4. Composition and chemical modification of foamed PS in the marine environment

Although the general behavior of foamed PS in the oceans and when beached has been addressed above, the precise impacts of the material in the marine setting are likely to be influenced by the presence, concentrations, and mobilities of the monomer (styrene), oligomers, reaction residues, and additives in the matrix, and any chemicals and contaminants that have been acquired from the environment.

Residues in foamed PS include Fe_2O_3, used as a catalyst in the production of styrene (43), and Zn stearate, often used to ensure uniform cell nucleation in the production of EPS (44). Additives are sometimes applied as a thin surface finish for protection but most are usually blended or molded into the raw material to ensure uniform concentration and are tailored to the specific requirements and applications of the material. For instance, addition of graphite can improve insulation properties of construction boards, various pigments may be employed to impart a range of different colors, and TiO_2 may be added to assist bacterial decomposition or as a pigment to provide a high refractive index (13;45). Plasticizers and biocides are not generally used in foamed PS but the stabilizer and antioxidant tris(4-nonylphenyl) phosphite, a source of the endocrine-disrupting nonylphenols, is sometimes added (46). Traces of other organic additives in EPS have also been mentioned or implied but have not been identified (47;48). However, because of the inherent flammability of foamed PS the most commonly employed additives are flame-retardants.

4.1. Hexabromocyclododecane

Flame-retardants are added to foamed PS destined for the construction industry but are also encountered in packaging material because one grade of material may be adopted for all production

196 (13). The most important flame-retardant used in EPS and XPS since the 1980s has been 1,2,5,6,9,10-
197 hexabromocyclododecane (HBCD) (49;50;51), whose physical, chemical, environmental, and
198 toxicological properties that are relevance to the discussion are given in Table S1. HBCD is added at
199 concentrations that are low relative to those of other halogenated compounds used to flame-retard
200 plastics; specifically, typical HBCD concentrations range from about 0.7 to 2.5% by weight of the raw
201 product, with XPS usually containing more of the retardant than EPS (52). Moreover, and unlike
202 flame-retarded plastics more generally and including polyethylene, foamed PS impregnated with
203 HBCD does not require the addition of antimony trioxide (Sb_2O_3) as a synergist to meet various
204 building code specifications (53). On health and environmental grounds, however, HBCD was
205 recently added to Annex A of persistent organic pollutants in the Stockholm Convention that require
206 elimination (54), effectively banning the production and use of the compound in PS foams for
207 buildings (55). The EU has also since introduced a low concentration limit of 0.1% (1000 mg kg^{-1}) by
208 weight for certain brominated compounds, including HBCD, above which items may not be recycled,
209 and a limit of 0.01% (100 mg kg^{-1}) above which products are not permitted for sale (56).

210 Recent focus has been on alternative flame-retardants, resins, or designs for foamed polystyrene,
211 with halogen-free retardants considered best for the environment and human health (57). However,
212 despite the restrictions on HBCD, the flame-retardant continues to be reported in an array of
213 foamed PS consumer products where fire suppression is neither required nor desired, including
214 food-contact articles and general purpose packaging, suggesting a continuing uncontrolled use or
215 recycling of the chemical (58;59). Moreover, it has been forecast that the amount of construction
216 and demolition waste containing HBCD will continue to increase until 2050 (13).

217 The historical use and contemporary recycling of HBCD, together with its persistence in the marine
218 environment, are also reflected by its presence in foamed PS encountered in beach litter and
219 functional maritime constructions throughout the ocean (60;61). For example, in the north Pacific,
220 HBCD was detected in nearly all samples analyzed (n > 200) that had been collected after the
221 chemical was listed in the Stockholm Convention, with concentrations ranging from 0.05 to 14,500
222 mg kg^{-1} (61). Some of the highest concentrations, and well above the EU low concentration limit,
223 were reported for aquaculture buoys where flame-retardancy is clearly unneccessary. Significantly,
224 because HBCD is not covalently bonded to the polymer, mobilization into the environment gradually
225 takes place (62), with a lipophilicity (log K_{ow} = 5.6; 63) ensuring that it will readily bind with organic
226 matter and concentrate in organisms.

227 *4.2. Styrene*

In theory, the polymerization of styrene results in repeating monomer units that are covalently bonded and difficult to break. In practice, however, this process is incomplete and the styrene monomer and oligomers may contaminate the final foamed PS product.

Styrene monomer released from PS is highly reactive towards cell systems and causes widespread metabolic damage, raising concerns about its migration from foamed PS packaging into food (46). In the environment, however, the monomer is rapidly volatilized and readily degraded and is not considered to bioaccumulate (64). On the other hand, the oligomers of styrene appear to present a very low risk to consumers through food packaging but are less mobile and more persistent in the environment (65), with the latter characteristics affording a potential means of assessing contemporary and historical pollution by PS (66). For example, Kwon et al. (67) measured various styrene contaminants (including the trimer, 2,4, 6-triphenyl-1-hexene, and the dimer, 2,4-diphenyl-1-butene) in coastal seawater and beach sand collected from different parts of the world and found that combined concentrations were variable but highest (and up to about 30 $\mu g\ L^{-1}$ in seawater and 30 $mg\ kg^{-1}$ in sand) along the most populated coastlines. Distributions were attributed to the leaching of the oligomers from weathered, foamed PS on beaches and their subsequent adsorption onto sand, with transfer to seawater taking place via desorption from contaminated sand or more directly through the leaching of the chemicals from floating PS litter. A more recent study suggested that oligomer concentrations in coastal seawater may also be augmented by inputs from contaminated catchment runoff (68).

4.3. Surface modification of foamed PS and acquisition of environmental contaminants

The weathering and chemical and biological fouling of foamed PS, evident in Figure 1e, result in significant modifications to the polymer surface. For example, measurements made by Zhang et al. (30) on virgin and beached EPS revealed an increase in specific surface area (from about 2 to 8 $m^2\ g^{-1}$), micropore area (from < 0.1 to 0.5 $m^2\ g^{-1}$), and point of zero charge (from 4.7 to 5.0) on weathering; by comparison, the specific surface area of aged polyethylene is just 0.13 $m^2\ g^{-1}$ (69). Not only do these characteristics confer a greater reactivity in the aqueous medium, the high positive buoyancy of foamed PS ensures that it is persistently exposed to a wide array of chemicals in the sea surface microlayer (Figure 2). This is a skin of water of 1 to 1000 μm thick enriched in various inorganic salts, hydrophobic or surface-active biogenic compounds, fuels and oils, and various trace contaminants of low solubility or that have been deposited from the atmosphere (70;71). Specifically, concentrations of some pollutants, like chlorinated hydrocarbons and heavy metals, may be up to 500 times higher in the microlayer compared with the underlying bulk water column (72). Hydrophobic chemicals have a propensity to interact with the embrittled and fractured

PS surface (47) and, while metal ions are known to readily adsorb onto hydrogenous precipitates on polyethylene (73-75), this has yet to be empirically demonstrated for foamed PS.

The acquisition of chemicals from the environment and the more general biological fouling also act to increase the net density of foamed PS. However, and in contrast to unfoamed plastics, this increase is not likely to be sufficient to cause a significant shift in buoyancy or effect sinking unless particles are considerably smaller than the diameter of component PS cells (76).

5. Impacts on marine organisms

Foamed PS does not represent a significant risk of entanglement to marine wildlife but can exert impacts through ingestion and interaction.

Ingestion of foamed PS may arise directly from the inadvertent consumption of material mistaken for food that is floating in the water column, deposited on beaches, trapped in macroalgae, or acting as a substrate-habitat, and indirectly via the consumption of contaminated prey. Consequently, ingestion has been documented in the stomach contents or fecal matter of a range of marine animals, including crustaceans, fish, birds, turtles, and mammals, and as exemplified in Table 2. Seabirds in particular are commonly observed to ingest foamed PS because floating fragments are similar in size and color to normal prey items like fish, fish eggs, and larvae (90). Birds, those that feed by dipping, fluttering above the surface, surface plunging, surface seizing, and scavenging are most likely to inadvertently ingest PS foam. In addition, distinctive marks on fragments of EPS and XPS retrieved from the shore suggest that some birds, including fulmars and gulls, peck at foamed PS, resulting in the ingestion of small particles (91;92). Pecking may be practiced out of curiosity or through confusion with the brittle and bright white, internal shells of cuttlefish that act as a supplemental source of calcium carbonate.

Many of the broad physical impacts resulting from the ingestion of foamed PS are likely to be common to those resulting from the ingestion of other plastics. These include intestinal blockage and injury to the digestive tract, with potential longer-term effects involving reduced body weight and fitness and slower growth. However, given foamed PS's relatively low density, smooth surface, high flexibility, and propensity to fragment, these impacts may be less severe or long-lasting than those effected by harder and sharper plastics like polyethylene. Plastic manufactured or fragmented to dimensions on the order of a few μm or less (nanoplastics) may also be captured by organisms as small as zooplankton and, in many cases, undergo internalization and translocation (93). Regular industrial (unfoamed) PS nanoparticles (density ~ 1.1 g cm^{-3}) have been frequently studied through

in vitro cultures with crustaceans, invertebrates, and fish and have resulted in a range of adverse effects, including delayed growth, repressed immunity, histopathological changes, behavioral changes, and decreased reproduction (94-97). It remains unclear, however, as to whether these effects can be extrapolated to positively-buoyant foamed PS should fragments be weathered down into nanoplastic dimensions.

An additional impact resulting from ingestion of foamed PS is the exposure to chemicals associated with the material through manufacturing or acquisition from the environment. Exposure is normally evaluated in vitro by subjecting test material to conditions that mimic the digestive environment and measuring chemical mobilization or bioaccessibility (as an upper bound estimate of bioavailability). Coffin et al. (48) determined the quantities of various organic additives released from sixteen different plastics subjected to solutions representative of the digestive environments of fish and seabirds as well as the estrogen-receptor activities of the resulting extracts using an in vitro cell line. Biological estrogenicity was significantly enhanced by extracts of three plastics (including EPS) in both digestive solutions but the precise additives or residues responsible were not among the chemicals characterized by the authors. Turner and Lau (60) report that neither Br (a proxy for HBCD) nor Zn (indicative of Zn stearate) were detected by ICP in extracts of aged, beached EPS subjected to a simulated avian digest, but that Fe oxide was measurably mobilized (presumably together with any contaminants associated with this phase) from the fouled surface. More sensitive HPLC analysis of HBCD in EPS buoys maintained in dark seawater, however, reveal that the brominated flame-retardant is slowly mobilized from the plastic (62) and, therefore, has the potential to be released under harsher digestive conditions of sea birds and other animals.

Interactions refer to a variety of impacts arising from contact of marine organisms with the material as an abiotic substrate and that can also, ultimately, result in plastic ingestion. For instance, certain organisms are able to colonize foamed PS as a rafting substrate, an effect that was originally documented for bacteria growing on EPS beads in the coastal waters of New England (98). More recently, Carson et al. (99) determined concentrations of bacteria up to 12,000 mm^{-2} on EPS fragments retrieved from the North Pacific Gyre; by comparison, maximum bacteria concentrations on polyethylene fragments from the same region were < 5000 mm^{-2}. It has been proposed that the initial colonization of foamed PS is more favorable than on unfoamed plastics because the greater rugosity of the former facilitates adhesion and affords protection (33). Foamed PS, however, displays relatively low species richness because of floating instability; that is, multiple positional changes that incur frequent exposure to air and direct sunlight negatively affect broader colonization (33). Consequently, free-floating, foamed PS likely acts as rafting and dispersing substrate for a limited number of organisms that grow during initial stages of community succession.

Jang et al. (100) describe marine mussels, *Mytilus galloprovincialis*, inhabiting the EPS of tethered aquaculture buoys off the coast of South Korea and demonstrated that HBCD is transferred from the substrate to the bivalve with resultant lipid weight concentrations of up to 5.2 mg kg^{-1}. The authors suggest that HBCD is bioaccumulated through the direct ingestion of fragmented EPS particles and via leaching of the chemical and its subsequent adsorption onto food particulates. Aquaculture buoy EPS also hosts a variety of polychaete worms, both at the surface and, via burrowing, within the internal structure (101). Worms both generate and consume debris, with an average of over 100 EPS particles reported in the digestive tracts of burrowing individuals.

Filter-feeding sphaeromatid isopods excavate burrows for their habitat and dense colonies are known to cause extensive damage to floating docks constructed of EPS (102). Burrowing may release large fragments of EPS that disperse isopods and are responsible for the generation of significant quantities of microplastics. Laboratory experiments conducted by Davidson (103) suggest that individual bioeroders can create several thousand particles when excavating a burrow, which is equivalent to 100,000 organisms per m^3 creating over 400 million particles. Microplastics may then be ingested by a range of organisms, including those that are cultured near to floats for human consumption.

Biotic Interactions with foamed PS also take place in reaches of the littoral zone that are never inundated but where debris from both marine sources and beach littering may accumulate. Poeta et al. (25) found that certain dunal plants were able to perforate EPS debris on a sandy beach situated along the Tyrrhenian coast of Italy. Although these observations were attributed to opportunistic events, the authors suggested that the thermal, mechanical, and water absorbing properties of EPS may be generally favorable for this kind of interaction and that the phenomenon might be more widespread on a global scale.

6. Emerging solutions to foamed PS waste generation and disposal

The discussions above highlight the problems of foamed PS in the marine environment arising from the quantity and diversity of applications of the material, its low density, ready fragmentation and dispersal in the ocean and littoral environments, the presence of harmful additives, and difficulty in retrieval of waste through, for example, beach cleans. Ultimately, countering these problems requires a reduction in the usage of foamed PS, modification or replacement of the material, or better management and recycling of PS-bearing waste.

Alternative materials to or designs of foamed PS require an ability to perform same function (e.g. insulation, fire-retardancy, strength, flotation) and yet be cost-effective, long-lasting, and/or more environmentally sustainable throughout their life cycle. Examples that are becoming more popular or that have been tested but are not widely employed are reported by Lassen et al. (13;104). In the construction sector, alternative materials are mineral and glass wools, phenolic foams, natural fibres, perlite, and wood fibreboards, with a modification of foamed PS that requires less material to achieve equivalent insulation achieved by the addition of graphite. Elsewhere, alternatives include corrugated cardboard for single use products, with polyethylene or polyethylene terephthalate lining where water absorption may be a problem, inflated air packets or molded pulp loose fill for single-use packaging, expanded polypropylene (a more robust foamed plastic) for multi-use packaging, and higher density EPS to enhance abrasion-resistance. In cities, states, and municipalities where restrictions or bans on single-use foamed PS products are in place, many compostable or readily recyclable alternatives have been introduced (19;105;106). Such alternatives also need to be considered for Europe where legislation is being drafted (Directive 2019/904, planned to be effective from July 2021) to ban single-use plastics that include EPS-XPS food and beverage containers (9). (In the UK, recent legislation bans specific single use plastics but thus far no specific mention is made of foamed PS products; 107).

In the marine sector, modifications or alternatives to conventional floats and buoys include air-filled plastics, plastic-coated EPS, or EPS contained by netting (108). However, there are additional problems with these constructions, such as increased cost, difficulties in tying to other structures, and enhanced biofouling. Incentive schemes for aquaculture farmers and fishermen to retrieve floating devices constructed of EPS have been trialed in Taiwan but have proven only partly successful, with suggestions that the imposition of a mandatory recovery rate might be more effective (26). Aside from the potential presence of HBCD in marine EPS, however, contamination of recovered material by, for example, salt, sand, oil, and chemical precipitates, precludes it from being recycled.

The construction and demolition industries generate significant quantities of foamed PS waste and fugitive particles through a variety of routes, including board cutting, and the storage and transport of material and offcuts. Measures to minimize the escapement of foamed PS from this sector include making employers more aware of environmental damage caused by the material, use of hot wires for cutting, careful separation of demolition waste, covering and securing waste containers, and incentivizing the return of unused material to the manufacturer (13). Demolition waste is of greater concern than contemporary construction waste because of the higher probability of material containing HBCD (109). The presence of this additive may also pose challenges and constraints on

how the material can be disposed of and recycled. Rapid screening methods based on portable X-ray fluorescence spectrometry have been developed that detect the presence and solubility of Br in foamed PS (HBCD is solvent-extractable while newer, 'safer' brominated compounds are not) (110). These methods could assist with decisions concerning the fate of demolition waste on site or as a waste disposal input control but to date these do not appear to have been applied on an industrial scale.

To summarize, foamed PS has a number of distinctive properties that renders it highly favorable for a wide range of applications across multiple sectors. However, it is this usage and these characteristics that ensure large quantities of foamed PS waste enter the marine environment and present a diversity of pervasive impacts. The chemical and biological risks of foamed PS are further compounded by the widespread occurrence of HBCD in historical and recycled products. Recommendations to reduce these risks and impacts relate to better management of foamed PS throughout its life cycle and replacing the material with more durable and sustainable alternatives.

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Supporting Information Available

This information is available free of charge via the Internet at http://pubs.acs.org.

Table S1 provides information on the physico-chemical and environmental properties of hexabromocyclododecane.

References

(1) Li, W.C., Tse, H.F., Fok, L. Plastic waste in the marine environment: A review of sources, occurrence and effects. Sci. Total Environ. 2016, 566-567, 333-349.

(2) Auta, H.S., Emenike, C.U., Fauziah, S.H. Distribution and importance of microplastics in the marine environment: A review of the sources, fate, effects, and potential solutions. Environ. Int. 2017, 102, 165-176.

(3) Miller, M.E., Kroon, F.J., Motti, C.A. Recovering microplastics from marine samples: A review of current practices. Mar. Pollut. Bull. 2017, 123, 6-18.

(4) Guo, X., Wang, J. The chemical behaviors of microplastics in marine environments: A review. Mar. Pollut. Bull. 2019, 142, 1-14.

(5) Garrity, S.D., Levings, S.C. Marine debris along the Caribbean coast of Panama. Mar. Pollut. Bull. 1993, 26, 317-324.

(6) Convey, P., Barnes, D.K.A., Morton, A. Debris accumulation on oceanic island shores of the Scotia Arc, Antarctic. Polar Biol. 2002, 25, 612-617.

(7) Otley, H., Ingham, R. Marine debris surveys at Volunteer Beach, Falkland Islands, during the summer of 2001/02. Mar. Pollut. Bull. 2003, 46, 1534-1539.

(8) Heo, N.W., Hong, S.H., Han, G.M., Hong, S., Lee, J., Song, Y.K., Jang, M., Shim, W.J. Distribution of small plastic debris in cross-section and high strandline on Heungnam Beach, South Korea. Ocean Sci. J. 2013, 48, 225-233.

(9) Black, J.E., Kopke, K., O.Mahony, C. Towards a circular economy: using stakeholder subjectivity to identify priorities, consensus, and conflict in the Irish EPS/XPS market. Sustainability 2019, 11, 6834 doi:10.3390/su11236834

(10) Gausepohl, H., Niessner, N. Polystyrene and styrene copolymers. In: Encyclopedia of Materials: Science and Technology (Second Edition), 2001, ed. K.H.J. Buschow, Elsevier, Amsterdam, pp7735-7741.

(11) Block, C., Brands, B., Gude, T. Packaging Materials 2. Polystyrene for Food Packaging Applications, 2017. ILSI Europe, Brussels, 36pp.

(12) Sulong, N.H.R., Mustapha, S.A.S., Rashid, M.K.A. Application of expanded polystyrene (EPS) in buildings and constructions: A review. J. Appl. Polym. Sci. 2019, 136 https://doi.org/10.1002/app.47529

(13) Lassen, C., Warming, M., Kjøholt, J., Jakobsen, L.G., Vrubliauskiene, N., Norichkov, B., Strand, J., Feld, L., Bach, L. Survey of Polystyrene Foam (EPS and XPS) in the Baltic Sea. Danish Fisheries Agency/Ministry of Environment and Food of Denmark, 2013, 166pp.

(14) Fujieda, S., Sasaki, K. Stranded debris of foamed plastic on the coast of Eta Island and Kurahashi Island in Hiroshima Bay. Nipp. Suisan Gakk. 2009, 71, 755-761.

(15) European Commission. Studies and Pilot projects in support of the Common Fisheries Policy. Lot 3: Evaluation of various marker buoy techniques for the marking of passive fishing gears. Report FISH/2007/03/Lot No. 3, 2007, Dublin, Ireland, 94pp.

(16) Hansen, A.A., Rodbotten, M., Lea, P., Rotabakk, B.T., Birkeland, S., Pettersen, M.K. Effect of transport packaging and repackaging into modified atmosphere on shelf life and quality of thawed Atlantic cod loins. Packag. Technol. Sci. 2015, 28, 925-938.

(17) Jang, M., Shim, W.J., Cho, Y., Han, G.M., Song, Y.K., Hong, S.H. A close relationship between microplastic contamination and coastal area use pattern. Water Res. 2020, 171, 115400 DOI: 10.1016/j.watres.2019.115400

(18) Hinojosa, I.A., Thiel, M. Floating marine debris in fjords, gulfs and channels of southern Chile. Mar. Pollut. Bull. 2009, 58, 341-350.

(19) Rosevelt, C., Los Huertos, M., Garza, C., Nevins, H.M. Marine debris in central California: Quantifying type and abundance of beach litter in Monterey Bay, CA. Mar. Pollut. Bull. 2013, 71, 299-306.

(20) Ali, R., Shams, Z.I., 2015. Quantities and composition of shore debris along Clifton Beach, Karachi, Pakistan. J. Coast. Conserv. 2015, 19, 527-535.

(21) Turner, A., Rees, A. The environmental impacts and health hazards of abandoned boats in estuaries. Reg. Stud. Mar. Sci. 2016, 6, 75-82.

(22) Esiukova, E. Plastic pollution on the Baltic beaches of Kaliningrad region, Russia. Mar. Pollut. Bull. 2017, 114, 1072-1080.

(23) Chitaka, T.Y., von Blottnitz, H. Accumulation and characteristics of plastic debris along five beaches in Cape Town. Mar. Pollut. Bull. 2019, 138, 451-457.

(24) Zhou, Q., Tu, C., Fu, C., Li, Y., Zhang, H., Xiong, K., Zhao, X., Li, L., Waniek, J.J., Luo, Y. Characteristics and distribution of microplastics in the coastal mangrove sediments of China. Sci. Total Environ. 2020, 703, 134807.

(25) Poeta, G., Fanelli, G., Pietrelli, L., Acosta, A.T.R., Battisti, C. Plastisphere in action: evidence for an interaction between expanded polystyrene and dunal plants. Environ. Sci. Pollut. Res. 2017, 24, 11856-11859.

(26) Chen, C.L., Kuo, P.H., Lee, T., Liu, C.H. Snow lines on shorelines: Solving Styrofoam buoy marine debris from oyster culture in Taiwan. Ocean Coast. Manag. 2018, 165, 346-355.

(27) Ekvall, M.T., Lundqvist, M., Kelpsiene, E., Šileikis, E., Gunnarsson, S.B., Cedervall, T. Nanoplastics formed during the mechanical breakdown of daily-use polystyrene products. Nanosc. Adv. 2019, 1, 1055.

(28) Hansen, E., Nilsson, N.H., Lithner, D., Lassen, C. Hazardous Substances in Plastic Materials. Oslo: COWI and the Danish Technological Institute on behalf of The Norwegian Climate and Pollution Agency, 2013, 150 pp.

(29) MatWeb. Material Property Data. http://www.matweb.com/search/datasheet.aspx?matguid=5f099f2b5eeb41cba804ca0bc64fa62f&ckck=1 accessed 4/20.

(30) Zhang, H., Wang, J., Zhou, B., Zhou, Y., Dai, Z., Zhou, Q., Chriestie, P., Luo, Y. Enhanced adsorption of oxytetracycline to weathered microplastic polystyrene: Kinetics, isotherms and influencing factors. Environ. Pollut. 2018, 243, 1550-1557.

(31) Allshouse, M.R., Ivey, G.N., Lowe, R.J., Jones, N.L., Beegle-Krause, C.J., Xu, J.T., Peacock, T. Impact of windage on ocean surface Lagrangian coherent structures. Environ. Fluid Mechan. 2017, 17, 473-483.

(32) Chubarenko, I., Bagaev, A., Zobkov, M., Esiukova, E. On some physical and dynamical properties of microplastic particles in marine environment. Mar. Pollut. Bull. 2016, 108, 105-112.

(33) Bravo, M., Astudillo, J.C., Lancecllotti, D., Luna-Jorquera, G., Valdivia, N., Thiel, M. Rafting on abiotic substrata: properties of floating items and their influence on community succession. Mar.Ecol. Progr. Ser. 2011, 439, 1-17.

(34) Brunner, K., Kukulka, T., Proskurowski, G., Law, K.L. Passive buoyant tracers in the ocean surface boundary layer: 2. Observations and simulations of microplastic marine debris. J. Geophys. Res. – Oceans 2015, 120, 7559-7573.

(35) Ward, C.P., Armstrong, C.J., Walsh, A.N., Jackson, J.H., Reddy, C.M. Sunlight converts polystyrene to carbon dioxide and dissolved organic carbon. Environ. Sci. Technol. Lett. 2019, 669-674.

(36) Yousif, E., Haddad, R. Photodegradation and photostabilization of polymers, especially polystyrene: Review. SpringerPlus 2013, 2, 393.

(37) Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Jung, S.W., Shim, W.J. Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type. Environ. Sci. Technol. 2017, 51, 4368-4376.

(38) Zhu, L., Zhao, S., Bittar, T.B., Stubbins, A., Li, D. Photochemical dissolution of buoyant microplastics to dissolved carbon: Rates and microbial impacts. J. Haz. Mater. 2020, 383, 121065.

(39) Ho, B.T., Roberts, T.K., Lucas, S. An overview on biodegradation of polystyrene and modified polystyrene: The microbial approach. Crit. Rev. Biotechnol. 2018, 38, 308-320.

(40) Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Jung, S.W., Shim, W.J. Corrections to "Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type". Environ. Sci. Technol. 2018, 52, 3831-3832.

(41) Efimova, I., Bagaeva, M., Bagaev, A., Kileso, A., Chubarenko, I.P. Secondary microplastics generation in the sea swash zone with coarse bottom sediments: Laboratory experiments. Front Mar. Sci. 2018, 5, 313 doi: 10.3389/fmars.2018.00313

(42) Chubarenko, I., Efimova, I., Bagaeva, M., Bagaev, A., Isachenko, I. On mechanical fragmentation of single-use plastics in the sea swash zone with different types of bottom sediments: Insights from laboratory experiments. Mar. Pollut. Bull. 2020, 150, 110726.

(43) Wünsch, J.R. Polystyrene: Synthesis, Production and Applications. RAPRA report, 2000, Shawbury, UK, 160 pp.

(44) European Union, Risk Assessment: Zinc distearate. EUR 21168 EN, 2008, Luxembourg, 188pp.

(45) Varnagiris, S., Girdzevicius, D., Urbonavicius, M., Milicus, D. Incorporation of SiO_2 and TiO_2 additives into expanded polystyrene. Energy Procedia 2017, 128, 525-532.

(46) Farrelly, T.A., Shaw, I.C. Polystyrene as Hazardous Household Waste. Intech Open Science, 2017, http://dx.doi.org/10.5772/65865

(47) Chen, Q., Zhang, H., Allgeier, A., Zhou, Q., Ouellet, J.D., Crawford, S.E., Luo, Y., Lang, Y., Shi, H., Hollert, H. Marine microplastics bound dioxin-like chemicals: Model explanation and risk assessment. J. Haz. Mater. 2019, 364, 82-90.

(48) Coffin, S., Huang, G.Y., Lee, I., Schlenk, D. Fish and seabird gut conditions enhance desorption of estrogenic chemicals from commonly-ingested plastic items. Environ. Sci. Technol. 2019, 53, 4588-4599.

(49) Li, L., Weber, R., Liu, J.G., Hu, J.X. Long-term emissions of hexabromocyclododecane as a chemical of concern in products in China. Environ. Int. 2016, 91, 291-300.

(50) Marvin, C.H., Gregg, T.T., Armitage, J.M., Arnot, J.A., McCarty, L., Copvaci, A., Palace, V. Hexabromocyclododecane: Current understanding of chemistry, environmental fate and toxicology and implications for global management. Environ. Sci. Technol. 2011, 45, 8613-8623.

(51) Arnot, J., McCarty, L., Armitage, J., Toose-Reid, L., Wania, F., Cousins, I. An evaluation of hexabromocyclododecane (HBCD) for Persistent Organic Pollutant (POP) properties and the

potential for adverse effects in the environment. European Brominated Flame Retardant Industry Panel, 2009, 199pp.

(52) Alaee, M., Arias, P., Sjodin, A., Bergman, A. An overview of commercially used brominated flame retardants, their applications, their use patterns in different countries/regions and possible modes of release. Environ. Int. 2003, 29, 683–689

(53) Papazoglou, E.S. Flame retardants for plastics, in: C.A. Harper (ed.), Handbook of Building Materials for Fire Protection, 2004, McGraw-Hill, New York, pp4.1-4.88.

(54) United Nations. Stockholm Convention on Persistent Organic Pollutants. C.N.934.2013.TREATIES-XXVII.15 (Amendment to Annex A), 2013. https://treaties.un.org/doc/Publication/CN/2013/CN.934.2013-Eng.pdf accessed 3/20.

(55) Schlummer, M., Mäurer, A., Wagner, S., Berrang, A., Fell, T., Knappich, F. Recycling of flame retarded waste polystyrene foams (EPS and XPS) granules free of hexabromocyclododecane (HBCD). Adv. Recycl. Waste Manag. 2017, 2.2 DOI: 10.4172/2475-7675.1000131

(56) European Commission. Regulation (EC) No 850/2004 of the European Parliament and of the Council of 29 April 2004 on Persistent Organic Pollutants and Amending Directive 79/117/EEC, 2016. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02004R0850-20160930 accessed 3/20.

(57) United Nations. Hexabromocyclododecane. http://chm.pops.int/Implementation/Alternatives/AlternativestoPOPs/ChemicalslistedinAnnexA/HBCD/tabid/5861/Default.aspx accessed 3/20.

(58) Rani, M., Shim, W.J., Han, G.M., Jang, M., Song, Y.K., Song, S.H. Hexabromocyclododecane in polystyrene based consumer products: an evidence of unregulated use. Chemosphere 2014, 110, 111-119.

(59) Abdullah, M.A.E., Sharkey, M., Berresheim, H., Harrad, S. Hexabromocyclododecane in polystyrene packaging: A downside of recycling? Chemosphere 2018, 199, 612-616.

(60) Turner, A., Lau, K.S. Elemental concentrations and bioaccessibilities in beached plastic foam litter, with particular reference to lead in polyurethane. Mar. Pollut. Bull. 2016, 112, 265-270.

(61) Jang, M., Shim, W.J., Han, G.M., Rani, M., Song, Y.K., Hong, S.H. Widespread detection of a brominated flame retardant, hexabromocyclododecane, in expanded polystyrene marine debris and microplastics from South Korea and the Asia-Pacific coastal region. Environ. Pollut. 2017, 231, 785-794.

(62) Rani, M., Shim, W.J., Jang, M., Han, M.G., Hong, S.H. Releasing of hexabromocyclododecanes from expanded polystyrenes in seawater -field and laboratory experiments. Chemosphere 2017, 185, 798-805.

(63) MacGregor, J.A., Nixon, W.B. Hexabromocyclododecane (HBCD): Determination of *n*-Octanol/Water Partition Coefficient. Wildlife International LTD. Project No. 439C-104, 1997. Chemical Manufacturers Association, Brominated Flame Retardant Industry Panel, Arlington, VA.

(64) PlasticsEurope. Styrene Monomer: Safe Handling Guide, 2018. Styrene Producers Association, Brussels, 57pp.

(65) Gelbke, H.P., Banton, M., Block, C., Dawkins, G., Eisert, R., Leibold, E., Pemberton, M., Puijk, I.M., Sakoda, A., Yasukawa, A. Risk assessment for migration of styrene oligomers into food from polystyrene food containers. Food Chem. Toxicol. 2018, 124, 151-167.

(66) Kwon, B.G., Moon, K.R. Physicochemical properties of styrene oligomers in the environment. Sci. Total Environ. 2019, 683, 216-220.

(67) Kwon, B.G., Koizumi, K., Chung, S.Y., Kodera, Y., Kim, J.O., Saido, K. Global styrene oligomers monitoring as new chemical contamination from polystyrene plastic marine pollution. J. Haz. Mater. 2015, 300, 359-367.

(68) Amamiya, K., Saido, K., Chung, S.Y., Hiaki, T., Lee, D.S., Kwon, B.G. Evidence of transport of styrene oligomers originated from polystyrene plastic to oceans by runoff. Sci. Total Environ. 2019, 667, 57-63.

(69) Fotopoulou, K.N., Karapanagioti, H.K. Surface properties of beached plastic pellets. Mar. Environ. Res. 2012, 81, 70-77.

(70) Lim, L., Wurl, O., Karuppiah, S., Obbard, J.P. Atmospheric wet deposition of PAHs to the sea-surface microlayer. Mar. Pollut. Bull. 2007, 54, 1212-1219.

(71) Li, S., Du, L., Zhang, Q., Wang, W. Stabilizing mixed fatty acid and phthalate ester monolayer on artificial seawater. Environ. Pollut. 2018, 242, 626-633.

(72) Wurl, O., Obbard, J.P. A review of pollutants in the sea-surface microlayer (SML): a unique habitat for marine organisms. Mar. Pollut. Bull. 2004, 48, 1016-1030.

(73) Holmes, L., Turner, A., Thompson, R.C. Interactions between trace metals and plastic production pellets under estuarine conditions. Mar. Chem. 2014, 167, 25-32.

(74) Richard, H., Carpenter, E.J., Komada, T., Palmer, P.T., Rochman, C.M. Biofilm facilitates metal accumulation onto microplastics in estuarine waters. Sci. Total Environ. 2019, 683, 600-608.

(75) Almeida, C.M.R., Manjate, E., Ramos, S. Adsorption of Cd and Cu to different types of microplastics in estuarine salt marsh medium. Mar. Pollut. Bull. 2020, 151, 110797.

(76) Ye, S., Andrady, A.L. Fouling of floating plastic debris under Biscayne Bay exposure conditions. Mar. Pollut. Bull. 1991, 22, 608-613.

(77) Gray, H., Lattin, G.L., Moore, C.J. Incidence, mass and variety of plastics ingested by Laysan (*Phoebastria immutabilis*) and Black-footed Albatrosses (*P. nigripes*) recovered as by-catch in the North Pacific Ocean. Mar. Pollut. Bull. 2012, 64, 2190-2192.

(78) Costa, L.L., Arueira, VF., da Costa, M.F., Di Beneditto, A.P.M., Zalmon, I.R. Can the Atlantic ghost crab be a potential biomonitor of microplastic pollution of sandy beaches sediment? Mar. Pollut. Bull. 2019, 145, 5-13.

(79) Iannilli, V., Di Gennaro, A., Lecce, F., Sighicelli, M., Falconieri, M., Pietrelli, L., Poet, G., Battisti, C. Microplastics in *Talitrus saltator* (Crustacea, Amphipoda): new evidence of ingestion from natural contexts. Environ. Sci. Pollut. Res. 2018, 25, 28725-28729.

(80) Kazour, M., Amara, R. Is blue mussel caging an efficient method for monitoring environmental microplastics pollution? Sci. Total Environ. 2019, 710, 135649.

(81) Goldstein, M.C., Goodwin, D.S. Gooseneck barnacles (*Lepas* spp.) ingest microplastic debris in the North Pacific Subtropical Gyre. PeerJ 2013, 1, e184 DOI: 10.7717/peerj.184

(82) Lenzi, J., Burgues, M.F., Carrizo, D., Machin, E., Texeira-de Mello, F. Plastic ingestion by a generalist seabird on the coast of Uruguay. Mar. Pollut. Bull. 2016, 107, 71-76.

(83) Zhu, C., Li, D., Sun, Y., Zheng, X., Peng, X., Zheng, K., Hu, B., Luo, X., Mai, B. Plastic debris in marine birds from an island located in the South China Sea. Mar. Pollut. Bull. 2019, 149, 110566.

(84) Phillips, R.A., Waluda, C.M. Albatrosses and petrels at South Georgia as sentinels of marine debris input from vessels in the southwest Atlantic Ocean. Environ. Int. 2020, 136, 105443.

(85) Avery-Gomm, S, O'Hara, P.D., Kleine, L., Bowes, V., Wilson, L.K., Barry, K.L. Northern fulmars as biological monitors of trends of plastic pollution in the eastern North Pacific. Mar. Pollut. Bull. 2012, 64, 1776-1781.

(86) Lusher, A.L., Hernandez-Milian, G., Berrow, S., Rogan, E., O'Connor, I. Incidence of marine debris in cetaceans stranded and bycaught in Ireland: Recent findings and a review of historical knowledge. Environ. Pollut. 2018, 232, 467-476.

(87) Rizzi, M., Rodrigues, F.I., Medeiros, L., Ortega, I., Rodrigues, L., Monteiro, D.S., Kessler, F., Proietti, M.C. Ingestion of plastic marine litter by sea turtles in southern Brazil: abundance, characteristics and potential selectivity. Mar. Pollut. Bull. 2019, 140, 536-548.

(88) Xiong, X., Chen, X., Zhang, K., Mei, Z., Hao, Y., Zheng, J., Wu, C., Wang, K., Ruan, Y., Lam, P.K.S., Wang, D. Microplastics in the intestinal tracts of East Asian finless porpoises (*Neophocaena asiaeorientalis sunameri*) from Yellow Sea and Bohai Sea of China. Mar. Pollut. Bull. 2018, 136, 55-60.

(89) Williams, R., Ashe, E., O'Hara, P.D. Marine mammals and debris in coastal waters of British Columbia, Canada. Mar. Pollut. Bull. 2011, 62, 1303-1316.

(90) Laist, D.W. Overview of the biological effects of lost and discarded plastic debris in the marine environment. Mar. Pollut. Bull. 1987, 18, 319-326.

(91) Cadée, G.C. Seabirds and floating plastic debris. Mar. Pollut. Bull. 2002, 44, 1294-1295.

(92) Battisti, C. Heterogeneous composition of anthropogenic litter recorded in nests of Yellow-legged gull (*Larus michahellis*) from a small Mediterranean island. Mar. Pollut. Bull. 2019, 150, 110682.

(93) Botterell, Z.L.R., Beaumont, N., Dorrington, T., Steinke, M., Thompson, R.C., Lindeque, P.K. Bioavailability and effects of microplastics on marine zooplankton: A review. Environ. Pollut. 2019, 245, 98-110.

(94) Cole, M., Lindeque, P., Fileman, E., Halsband, C., Galloway, T.S. The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*. Environ. Sci. Technol. 2015, 49, 1130-1137.

(95) Yin, L.Y., Chen, B.J., Xia, B., Shi, X.T., Qu, K.M. Polystyrene microplastics alter the behavior, energy reserve and nutritional composition of marine jacopever (*Sebastes schlegelii*). J. Haz. Mater. 2018, 360, 97-105.

(96) Bergami, E., Emerenciano, A.K., Gonzalez-Aravena, M., Cardenas, C.A., Hernandez, P., Silva, J.R.M.C., Corsi, I. Polystyrene nanoparticles affect the innate immune system of the Antarctic sea urchin *Sterechinus neumayeri.* Polar Biol. 2019, 42, 743-757.

(97) Messinetti, S., Mercurio, S., Scari, G., Pennati, A., Pennati, R. Ingested microscopic plastics translocate from the gut cavity of juveniles of the ascidian *Ciona intestinalis*. Eur. Zoo. J. 2019, 86, 189-195.

(98) Carpenter E.J., Anderson, S.J., Harvey, G.R., Miklas, H.P., Peck, B.B. Polystyrene spherules in coastal waters. Science 1972, 178, 749-750.

(99) Carson, H.S., Nerheim, M.S. Carroll, K.A., Eriksen, M. The plastic-associated microorganisms of the North Pacific Gyre. Mar. Pollut. Bull. 2013, 75, 126-132.

(100) Jang, M., Shim, W.J., Han, G.M., Rani, M., Song, Y.K., Hong, S.H. Styrofoam debris as a source of hazardous additives for marine organisms. Environ. Sci. Technol. 2016, 50, 4951-4960.

(101) Jang, M., Shim, W.J., Han, G.M., Song, Y.K., Hong, S.H. Formation of microplastics by polychaetes (*Marphysa sanguinea*) inhabiting expanded polystyrene marine debris. Mar. Pollut. Bull. 2018, 131, 365-369.

(102) Harrison, K., Holdich, D.M. *Hemibranchiate sphaeromatids* (Crustracea, Isopoda) from Queensland, Australia, with a world-wide review of the genera discussed. Zoo. J. Linn. Soc. 1984, 81, 275–387.

(103) Davidson, T.M. Boring crustaceans damage polystyrene floats under docks polluting waters with microplastic. Mar. Pollut. Bull. 2012, 64, 1821-1828.

(104) Lassen, C., Maag, J., Hoibye, L., Vesterlykke, M. Climate and Pollution Agency, 2011. Alternatives to the Use of Flame Retarded EPS in Buildings. Report TA2827, 2011, Climate and Pollution Agency, Oslo, 98pp.

(105) Blackwood, K. US capital bans Styrofoam food packaging. Front. Ecol. Environ. 14, 7-7.

(106) Thaysen, C., Stevack, K., Ruffolo, R., Poirier, D., De Frond, H., DeVera, J., Sheng, G., Rochman, C.M. Leachate from expanded polystyrene cups is toxic to aquatic invertebrates (*Ceriodaphnia dubia*). Front. Mar. Sci. 5, 71 doi: 10.3389/fmars.2018.00071.

(107) Let's Recycle. UK and EU prepare for single use plastic bans. https://www.letsrecycle.com/news/latest-news/uk-and-eu-prepare-for-single-use-plastic-bans/ accessed 4/20.

(108) Lee, J., Hong, S., Jang, Y.C., Lee, M.J., Kang, D., Shim, W.J. Finding solutions for the Styrofoam buoy debris problem through participatory workshops. Mar. Pol. 2015, 51, 182-189.

(109) Nie, Z.Q., Yang, Z.L., Fang, Y.F., Tang, Z.W., Wang, X.R., Die, Q.Q., Gao, X.B., Zhang, F.S., Wang, Q., Huang, Q.F. Environmental risks of HBCDD from construction and demolition waste: A contemporary and future issue. Environ. Sci. Pollut. Res. 2015,22, 17249-17252.

(110) Schlummer, M., Vogelsang, J., Fiedler, D., Gruber, L., Wolz, G. Rapid identification of polystyrene foam wastes containing hexabromocyclododecane or its alternative polymeric brominated flame retardant by X-ray fluorescence spectroscopy. Waste Manag. Res 2015, 1-9, DOI: 10.1177/0734242X15589783

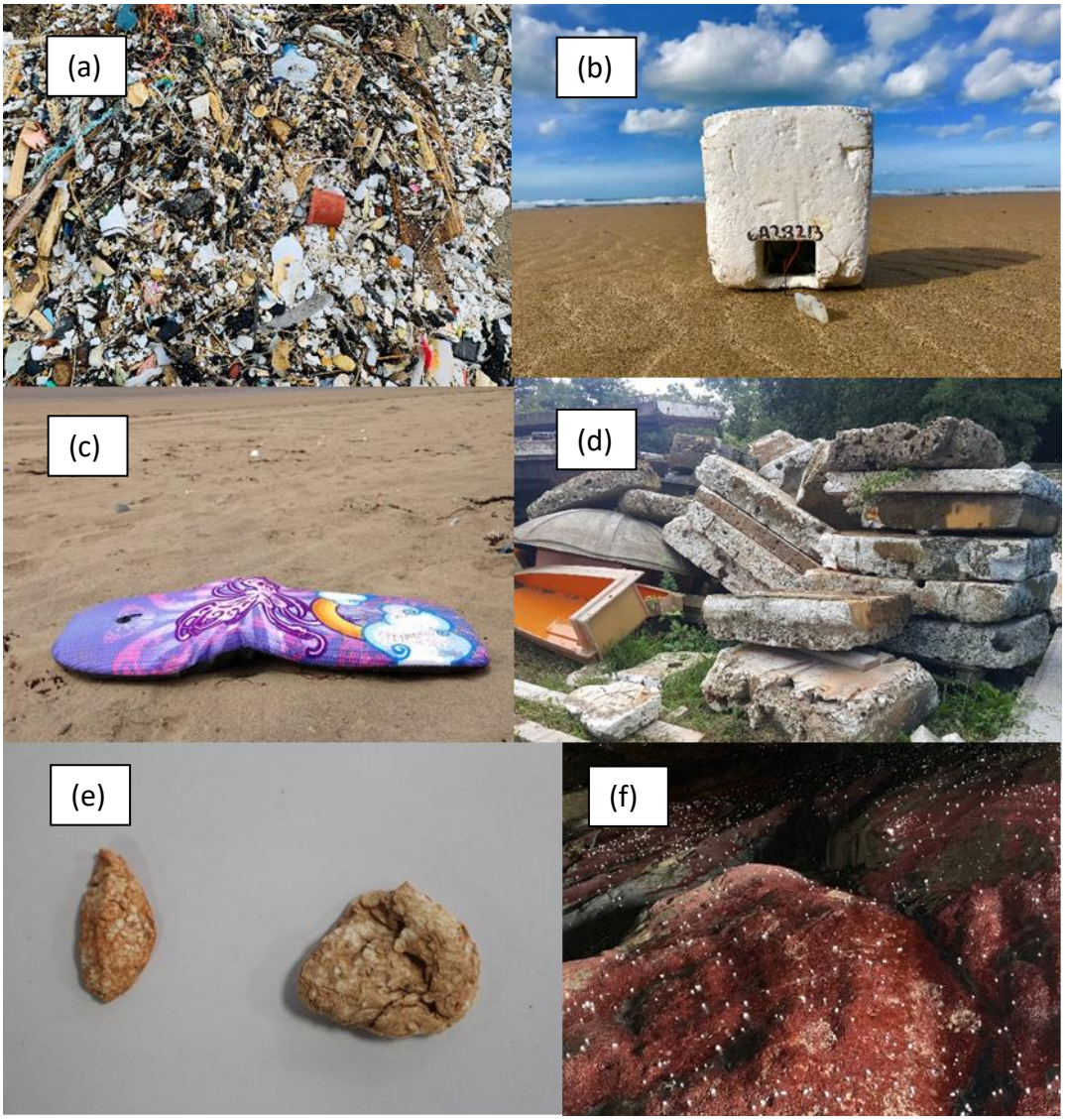

Figure 1: Foamed PS captured around or retrieved from the coast of south-west England. (a) An abundance of EPS and XPS amongst litter along the strandline; (b) EPS remains of a weather balloon; (c) a discarded EPS surfboard; (d) stacked EPS slabs used as boat stands; (e) fouled and rounded fragments of beached EPS and XPS litter; (f) EPS beads scattered at the base of a cliff. Photographs courtesy of Claire Wallerstein and Tracey Williams.

728 Table 1: The properties of foamed PS of relevance to the discussion. Data are shown for a single,
729 unspecified EPS product or a range of EPS products.

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Property	mean ± 1 sd or range	source
Physical		
Density	0.01 to 0.19 g cm^{-3}	10
Permeability	0.5 to 3.5	29
Water absorption	0.03 to 9.0%	29
Pore volume	0.02 ± 0.005 cm^3 g^{-1}	30
Average pore diameter	39.3 ± 0.5 nm	30
Mechanical		
Tensile strength, ultimate	0.08 to 0.91 MPa	29
Compressive yield strength	0.069 to 10.9 MPa	29
Tear strength	1.05 to 5.29 kN m^{-1}	29
Surface		
BET specific surface area	2.03 ± 0.04 m^2 g^{-1}	30
Point of zero charge	4.7 ± 0.2	30

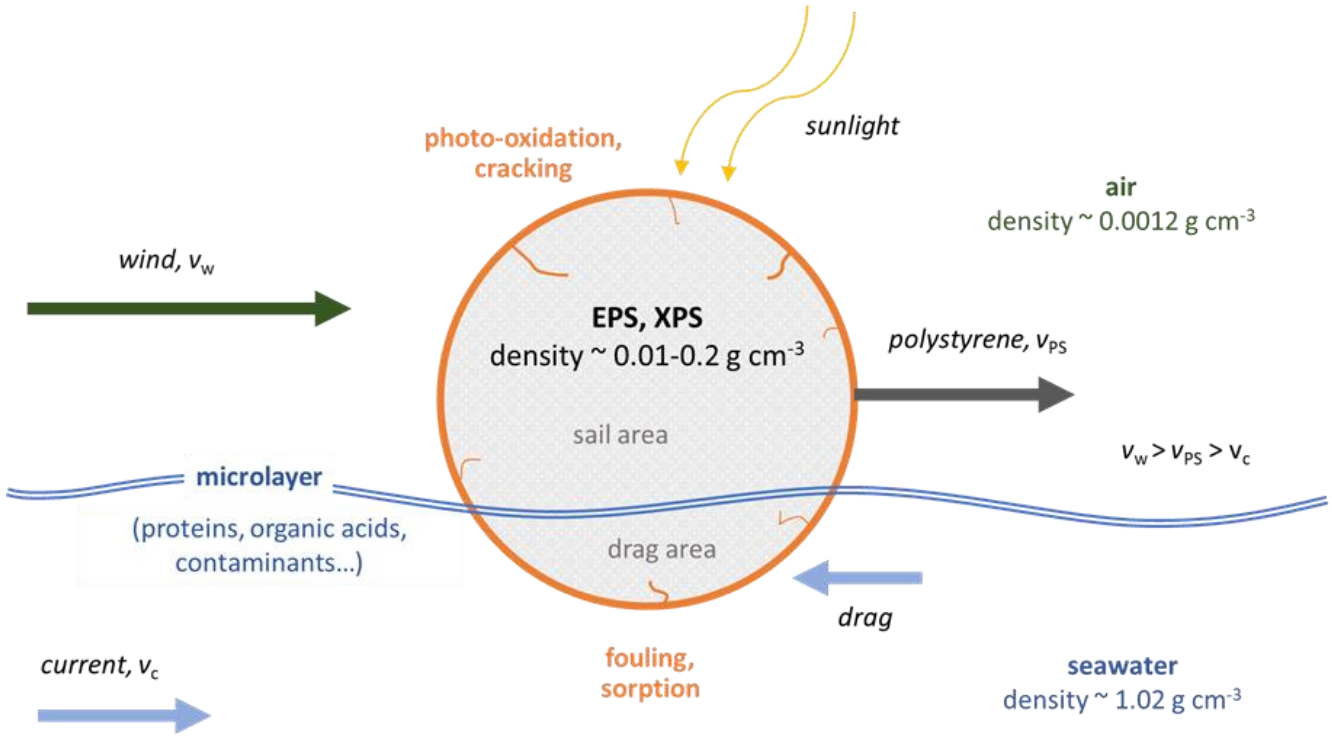

Figure 2: Conceptual representation of the effects and forcing mechanisms acting on a foamed PS sphere in the ocean.

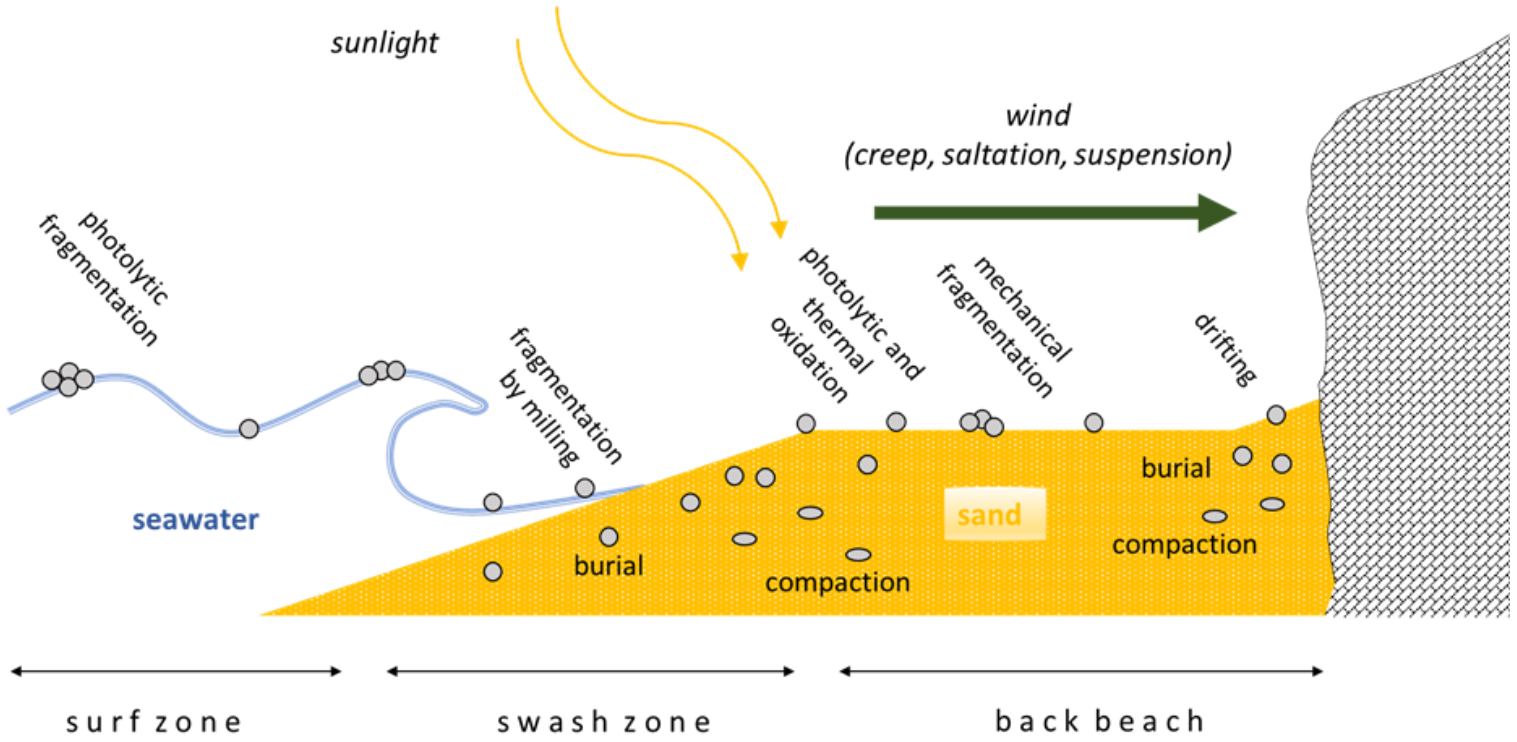

Figure 3: Conceptual representation of the effects and forcing mechanisms acting on foamed PS fragments in the sandy littoral zone.

770 Table 2: Examples of reports of the ingestion of foamed PS by marine wildlife.

Animal	Location	Material description	Reference
Black footed albatross	Central Pacific	foam, including PS	79
Laysan albatross	Central Pacific	foam, including PS	79
Atlantic ghost crab	Southwest Atlantic	XPS	80
Sand hopper	Mediterranean	EPS	81
Blue mussel	English Channel	foamed PS	82
Gooseneck barnacles	North Pacific Subtropical Gyre	foamed PS	83
Kelp gull	Southwest Atlantic	foamed PS	84
Red-footed booby	South China Sea	foamed PS	85
Various albatrosses and petrels	South Atlantic	foamed PS	86
Northern fulmar	Northeast Pacific	Styrofoam	87
Northern fulmar	Northeast Atlantic	expanded PS	88
Green turtle	Southwest Atlantic	XPS	89
Loggerhead turtle	Southwest Atlantic	XPS	89
Narrow-ridged finless porpoise	Yellow Sea-Bohai Sea	foamed PS	90
Elephant seal	Northeast Pacific	Styrofoam	91
Steller sea lion	Northeast Pacific	Styrofoam	91
Polychaete worms	Yellow Sea	EPS	103

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